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BEHAVIOR OF CEMENTED SANDS—I. TESTING

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SUMMARY

This paper is accompanied by a study on constitutive modelling issues of cemented sands. The concentration here is on experimental issues related to the triaxial testing of cemented sands. A preliminary investigation is performed aiming to identify potential effects of specimen size and slenderness on the stress–strain–strength characteristics of cemented sands. A comprehensive experimental study follows where clean sand specimens, as well as specimens with 2, 4 and 6 per cent cement content, are tested. The aim of the study is to examine the effects of cement content and confinement on the shear strength, stiffness, softening and dilation characteristics of cemented sand. © 1997 by John Wiley & Sons, Ltd.

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Key words: cemented sand; size; slenderness; triaxial testing; stress-strain

INTRODUCTION

The study of cemented soils is of significant interest to geotechnical engineers. Soil cementation can be found naturally, or induced artificially for the purpose of improving the bearing capacity of weak soils. Cementation plays a significant role in the engineering behaviour of soils, and has been investigated by geotechnical engineers in the United States and around the world.[1–5] Most published research concentrates on testing cemented soils, and developing appropriate simple Mohr–Coulomb-type failure criteria. However, only limited information on experimental details has been reported, and the intricacies of brittle material testing *seem* to have been ignored. The rather large body of related literature on testing has not been accompanied by an equal effort in constitutive modelling. Even though failure criteria of cemented soils are often discussed, complete constitutive models are rather rare[6,7] and are direct extensions of established soil models, with an added cohesion component.

The research that is reported here is based on a project undertaken at The University of Arizona to investigate, test and model the behaviour of cemented sands. The experimental phase of this project aims to identify some problems involved with triaxial testing of cemented soils, correct them and provide a credible set of experimental data to describe the engineering behaviour of cemented soils. The modelling phase aims to develop a constitutive model that recognizes the multi-phase nature of cemented soils.

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The current paper presents the findings of the experimental phase of this endeavor, while the companion paper[8] presents the developed constitutive model, and demonstrates its ability to predict the behaviour of a cemented soil.

CRITICAL LITERATURE REVIEW

Small amounts of cement content in sands are often neglected in geotechnical design as a conservative approach. Nevertheless, recent work has shown that the stability of foundations and slopes can be significantly influenced and enhanced by the presence of small amounts of cement content. Added benefits on the liquefaction resistance of sands due to cementation have also been reported.[3,4] Understanding the behaviour of cemented soils under static and dynamic loading conditions is thus of significant interest to geotechnical engineers.

A number of experimental studies on the engineering behaviour of cemented soils have been reported in the literature. The reported results have often contradicted each other, leaving the general picture of the behaviour of cemented soils somewhat unclear. For example, all experimental reports agree that an increase of cement content results in increase of cohesion. However, there is no general agreement regarding the effects of cement content on the peak friction angle ϕ. Whereas some researchers reported increase of the friction angle due to cement content,[9–11] others[12–15] reported a parallel movement of the failure envelope (i.e. no change in ϕ) caused by increase of cement content.

A careful study of all these reports reveals certain *potential* deficiencies. These include the following:

(a) *Reported testing with specimens of diameter sizes 3.5–3.8 cm.* Since laboratory testing is meant to simulate the infinitesimal *continuum* element, the size of the specimen must be large compared to its grain. Specimens with diameter of 3.5 cm are considered too small for accurate testing of sandy soils.[16] In cemented soils, the 'effective grain size' may be even larger due to conglomerations that are formed, which make the results of 3·5 cm diameter testing even more questionable.

(b) *Reported testing of specimens with a slenderness ratio* (*height to diameter*) *of at least two.* Due to initial inhomogeneities of cemented soil specimens, the formation of shear bands initiated at weak (surface) points are easily developed for slender specimens. Thus, premature failure may occur and the post-peak recordings, affected by shear bands are questionable. A more extensive discussion on the subjected is presented later on the section of slenderness effects.

(c) *No specimen end friction precautions during compression testing were reported.* Since end lubrication and related issues are normally reported as a significant part of geotechnical testing, the authors tend to believe that the lack of such discussion may imply lack of end lubrication. Even though *end effects* on clean sand specimens with 2 : 1 slenderness ratio may be considered moderate, they can be significant for brittle materials such as cemented sands.

The aim of the present study is to obtain a better understanding of the behaviour of cemented sands and eventually develop a constitutive model that addresses the multi-phase nature of cemented sands. For this purpose, an experimental program was designed that is concerned with the issues raised above. The results of this effort are reported in this paper, while the modelling of these results is presented in the companion paper.[8]

EXPERIMENTAL PLANNING

The experimental program implemented here is based on the following principles: (1) the specimen must have lubricated ends; (2) the specimen must be as large (in diameter) as possible; and (3) the specimen must be as short as possible. It is understood, however, that end effects due to friction,* and grain size put a lower limit to the specimen height. Further clarification related to the last issue is presented in the section of slenderness effects.

Based on these principles, an *exploratory* series of experiments was conducted using specimens with 4 per cent cement content. The purpose of these tests was to identify a specimen geometry that can produce reliable experimental results. An *investigative* series of triaxial compression tests followed aiming to provide a general understanding of the effects of cement content on soil behaviour.

Materials and sample preparation

The index properties of the sand used in this study can be summarized as given in Table I. The cementing agent is Portland cement type I–II (commercial grade). Complete details of the material properties and sample preparation can be found in Reference 17.

Sand, cement and water were mixed in the desired proportions to produce a uniform paste that was then poured into plastic molds of the desired dimensions. The inner surface of the molds was lubricated to reduce adhesion. The paste was poured in 5 cm thick layers and tapped using the standard Proctor compaction hammer. The details of this process can be found in Reference 17.

Pure sand specimens were prepared within a mould-rubber membrane system using pluvial deposition.

Pure sand specimens as well as cemented specimens with cement content 2, 4 and 6 per cent by weight were prepared. All specimens had a dry density of approximately 1·60 Mg/m^3 with the exception of the 2 per cent specimens that had a dry density of 1·50 Mg/m^3. The tests were performed in a triaxial compression apparatus under dry conditions.

Exploratory tests

Specimens with diameter of 3·5 cm were not considered. Most modern geotechnical laboratories currently conduct triaxial experiments on specimens of 5 or 6·4 cm diameter. To examine the

Table I. The index properties of the sand

Classification (USCS)	SP
Coefficient of curvature, C_c	0·76
Coefficient of uniformity, C_u	2·3
Medium grain size D_{50}	0·67 mm
Maximum void ratio e_{max}	0·93
Minimum void ratio e_{min}	0·60

* Even though measures are taken to minimize the end friction, it is recognized that some residual friction remains, thus having some effect on the specimen behaviour

appropriateness of such specimens, triaxial compression tests were performed on specimens with diameters of 5 and 10 cm.

To examine the effects of specimen slenderness, triaxial compression tests were conducted with slenderness ratios SR $=$ height/diameter ranging from 0·75 to 2·0. Specimens with SR $=$ 2·0 and diameter $D = 10$ cm could not be tested due to size limitations of the triaxial cells of the Geotechnical Laboratory, Department of Civil Engineering and Engineering Mechanics, The University of Arizona. Thus, for specimens with diameter of 10 cm, the maximum height was 19 cm (SR $=$ 1·9).

End lubrication. All tests were conducted using Teflon sheets on both ends between the loading caps and the specimens. Further friction reduction was obtained through the use of petroleum jelly (vaseline) that was applied between the Teflon sheets and the specimens. Although no means of measuring the interface shear stresses was available, indirect proof of the effectiveness of the lubrication was obtained through uniform measurements of lateral deflections at the ends and the middle of the specimens.

Specimen size effects. The effects of specimen size are qualitatively established.† In a simple way, one can state that, everything else being equal, *the larger the specimen size is, the more reliable the testing results are*. In general, smaller specimens exhibit stiffer and stronger behaviour than the larger specimens when tested under similar stress paths. To examine the effects of specimen size for cemented sands, tests were conducted with specimen diameters of 5 and 10 cm.

Figures 1 and 2 illustrate the size effects for specimens with a slenderness ratio SR $=$ 2·0, while Figures 3 and 4 illustrate the size effects for specimens with a slenderness ratio SR $=$ 1·0. In all cases, it becomes clear that the 5 cm specimens are stronger than the 10 cm diameter specimens. The confining pressure of 15 kPa, applied on certain specimens, is meant to approximate the unconfined compression test. In an effort to obtain more reliable volumetric strain information, the 'unconfined compression' tests were performed in a triaxial cell mounted to to a triaxial testing apparatus, which operates with a minimum confining pressure of 15 kPa.

In most cases, the 5 cm diameter specimens exhibit stronger degradation (softening) during post-peak straining. This general trend was not always clear for low confinement pressures (Figures 1 and 3) due to surface crack development, which is more intense for low confinement pressures, resulting in inhomogeneous and less reliable stress–strain curves. Further discussion on this subject is presented in the section of slenderness effects.

The appropriateness of the 5 cm diameter specimens to obtain acceptable information for design purposes is left to the judgement of the reader. However, for the purposes of the current study, further testing was conducted only on specimens with 10 cm diameter.

Slenderness effects. In addition to the size, the slenderness ratio of specimens influences the stress–strain characteristics of brittle materials such as cemented specimens. This can be seen by

† The term 'specimen size' is used here to compare specimens of the *same* slenderness ratio. For example, a specimen with $D = 5$ cm and $H = 10$ cm is smaller than a specimen with $D = 10$ cm and $H = 20$ cm

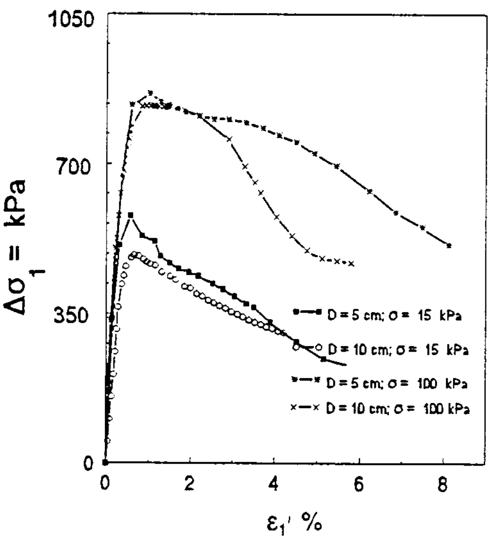

Figure 1. Size effects for specimens with SR = 2·0 : case of low confinement

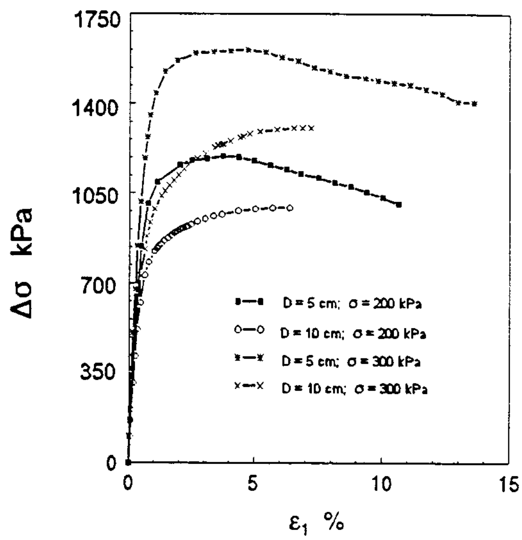

Figure 2. Size effects for specimens with SR = 2·0 : case of high confinement

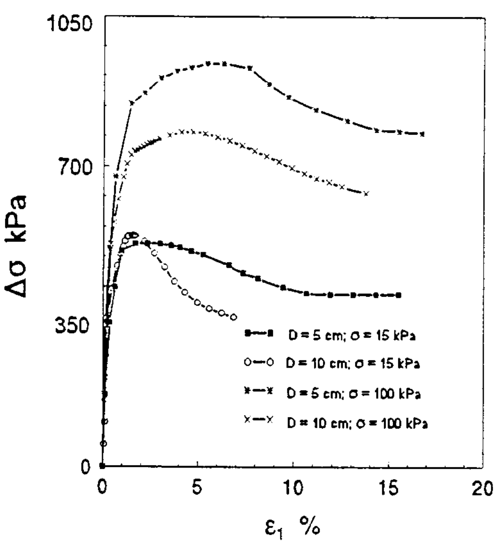

Figure 3. Size effects for specimens with SR = 1·0 : case of low confinement

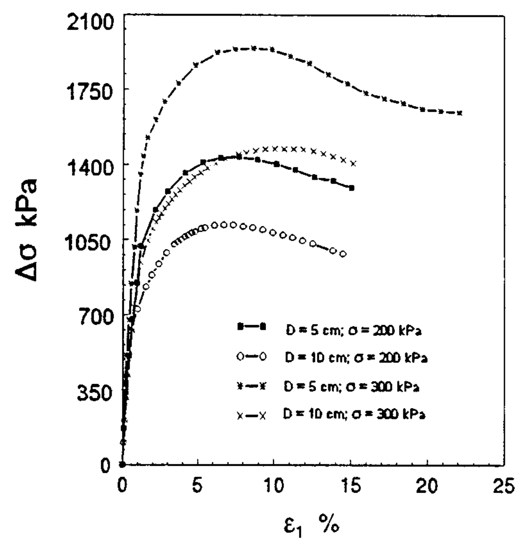

Figure 4. Size effects for specimens with SR = 1·0 : case of high confinement

comparing Figures 5–8 for cemented sand specimens with 4% cement content and confining pressures of 200 and 300 kPa. Tests were also performed for confining pressures of 15 and 100 kPa, which yielded similar results but are not shown here for economy of space. For a complete presentation of the experimental results the reader is referred to Reference 17. It

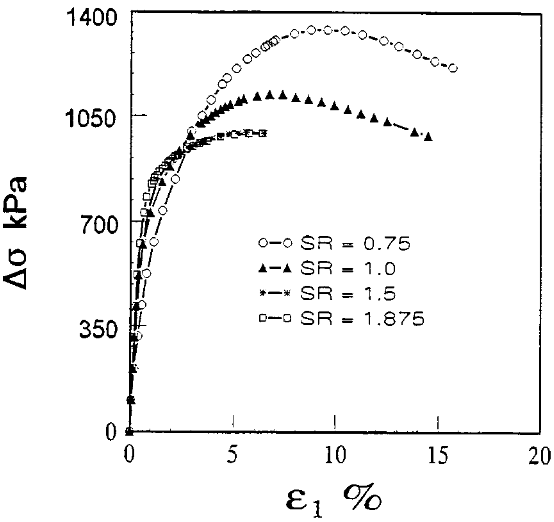

Figure 5. Effects of SR on shear strength of cemented soil with 4% cement content. Confining pressure $\sigma_3 = 200$ kPa

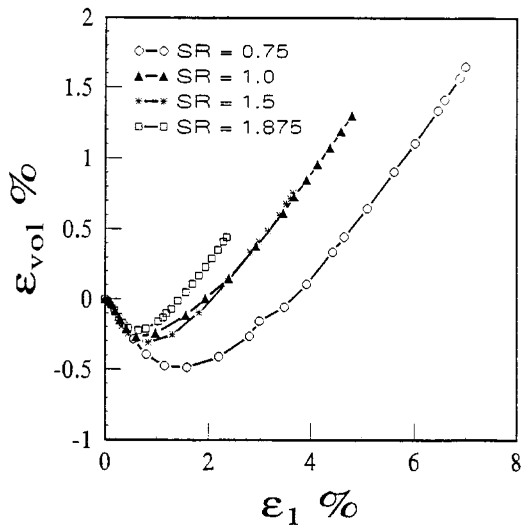

Figure 6. Effects of SR on volumetric response of cemented soil with 4% cement content. Confining pressure $\sigma_3 = 200$ kPa

becomes clear that the shorter specimens are stronger as is illustrated in Figures 5 and 7, and summarized in Figures 9 and 10. It is also clear that the longer specimens dilate earlier, even though the final rate of dilatation is not affected. However, the question remains as to which SR is more representative of the material behaviour. The development of surface-initiated failure is important for the derivation of the appropriate conclusions. In a significant work presented by

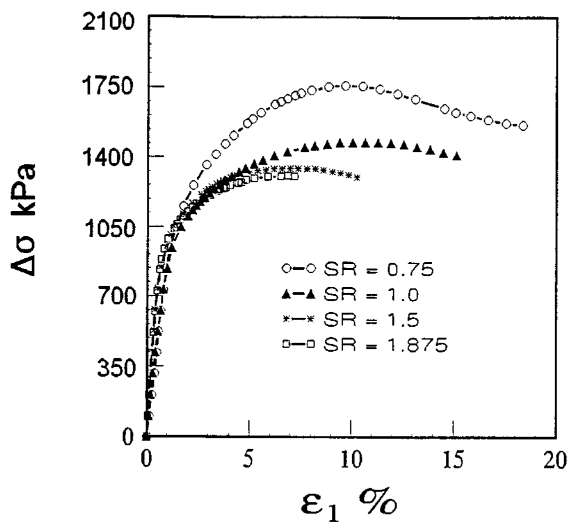

Figure 7. Effects of SR on shear strength of cemented soil with 4% cement content. Confining pressure $\sigma_3 = 300$ kPa

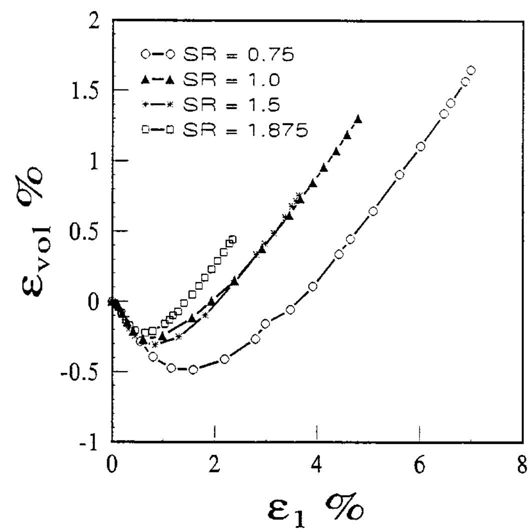

Figure 8. Effects of SR on volumetric response of cemented soil with 4% cement content. Confining pressure $\sigma_3 = 300$ kPa

Yukutake,[18] a series of triaxial tests were performed on granite. It was found that during shearing, numerous cracks were developed near the specimen surface, and propagated toward the middle of the specimens as illustrated in Figure 11. It can be seen clearly that a non-uniform micro-fracture field is generated within the specimen which eventually leads to the typical shear band that is generated during triaxial testing of brittle materials. To reduce the effects of such surface-initiated

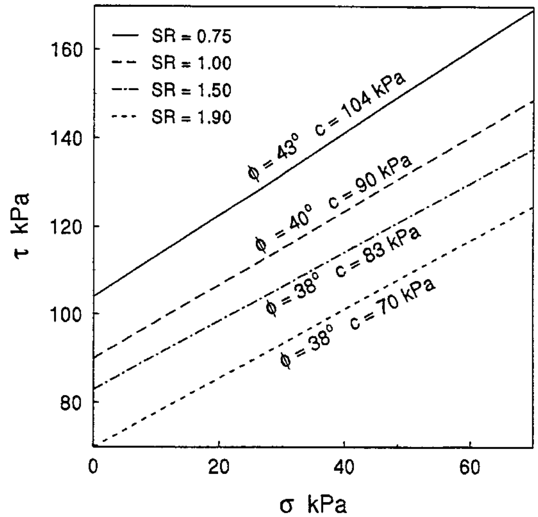

Figure 9. Effect of SR on Mohr–Coulomb failure envelope of cemented soil with 4% cement content

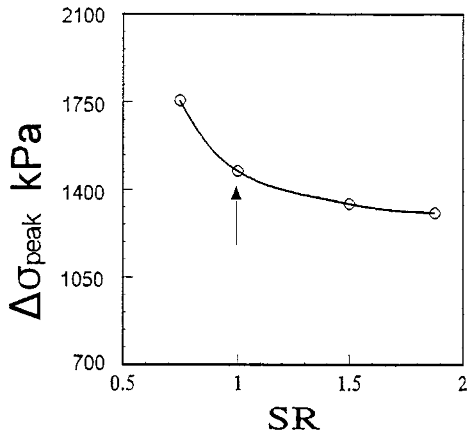

Figure 10. Effects of SR on peak strength of cemented soil with 4% cement. Confining pressure $\sigma_3 = 300$ kPa

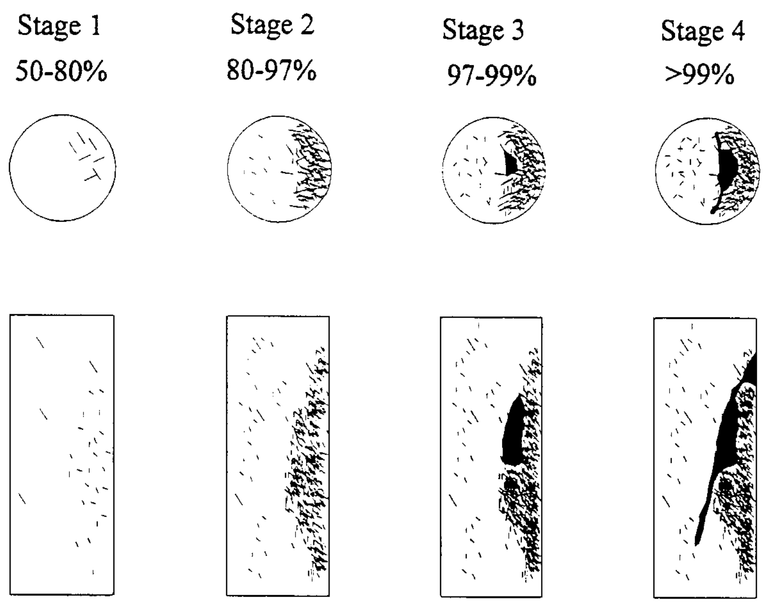

Figure 11. Schematic fracturing process of granite specimen under triaxial loading

failure, short specimens are preferable. The reason becomes apparent through the illustration presented in Figure 12. Shearing of a tall specimen generates a large degraded volume of the sample that can speed up the failure process. Shearing of a short specimen however results in

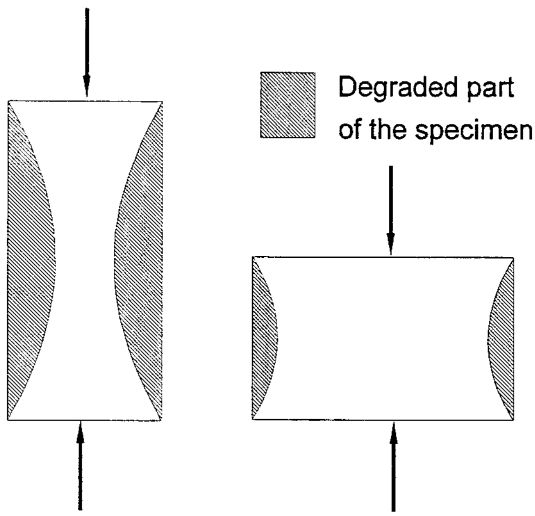

Figure 12. Schematic of the effects of degraded area close to the specimen surface

a significantly smaller (in proportion) volume of degraded material thus providing a more representative material response. Care must be taken however to avoid specimens that are *too short*. Such specimens can provide unrealistic response if the interface friction with the cap and the base pedestal is significant. End friction provides additional confinement, and a false sense of added shear strength. In addition, specimens that are too short may have grain-size-related problems.[‡] Consider the extreme case of testing a specimen that is one grain size tall. Triaxial testing of such specimen yields the compression strength of the individual grains and thus provides unrealistic results.

Reduction of SR from 1·875 to 1·0 is characterized by a mild, almost linear increase in shear strength (Figure 10). Further reduction to SR = 0·75 results in rapid non-linear increase in shear strength. It is believed that the latter may be due to interface friction,[§] as was indicated by the slight barrelling of the specimen at large deformations. In view of the above, the value of SR = 1 is considered to be fairly free of the problems of surface-initiated failure encountered in the *too long* samples, and the friction and end interactions encountered in the *too short* specimens.

PRESENTATION OF EXPERIMENTAL RESULTS

The experimental program presented here is designed to examine the stress–strain–strength characteristics of cemented sands, and the related effects of confinement and degree of cement content. To examine these effects, triaxial tests were performed on the cemented sand with cement contents 2, 4 and 6 per cent. Additional triaxial tests on clean sand were also performed

[‡] That is, the height of the specimen may be too small for the grain size

[§] It is understood that end lubrication reduces but does not eliminate the end friction entirely

for reference. All triaxial compression tests presented here were performed on specimens with diameter $D = 10$ cm and height $H = 10$ cm. The order of presentation of the results aims to emphasize first the effects of cement content, and then the effects of confinement.

Typical stress–strain results for various degrees of cement content and different levels of confinement are presented in Figures 13, 15, 17 and 19. The corresponding volumetric relations are presented in Figures 14, 16, 18 and 20.

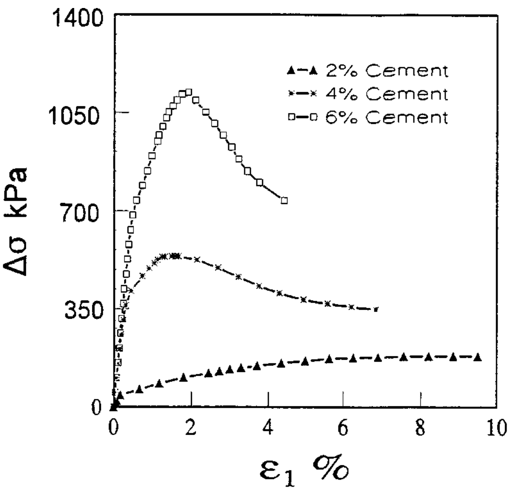

Figure 13. Effects of cement content on ε–σ relations for $\sigma_3 = 15$ kPa

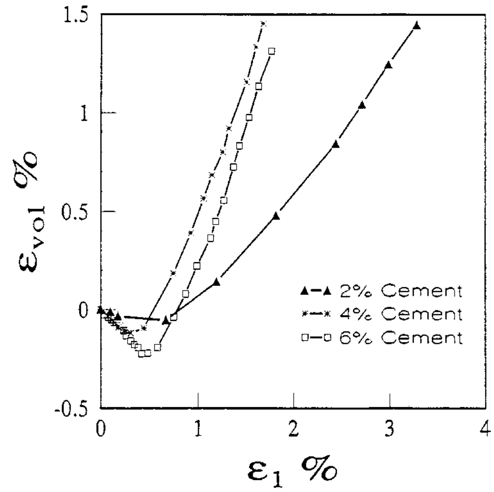

Figure 14. Effects of cement content on volumetric strain relations for $\sigma_3 = 15$ kPa

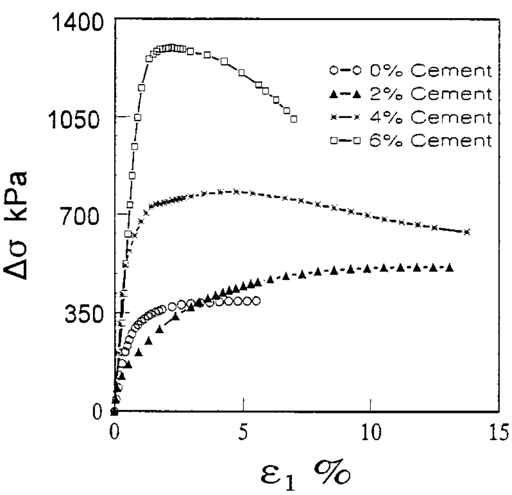

Figure 15. Effects of cement content on ε–σ relations for $\sigma_3 = 100$ kPa

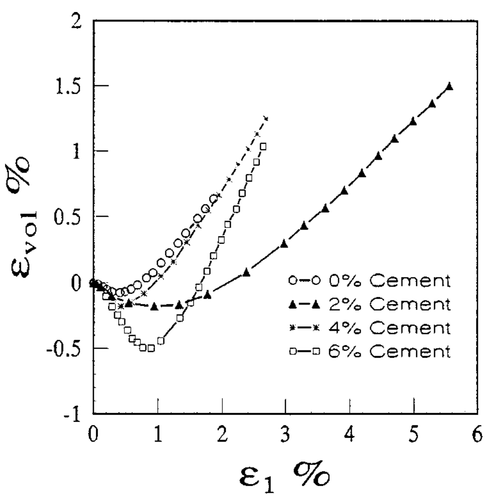

Figure 16. Effects of cement content on volumetric strains for $\sigma_3 = 100$ kPa

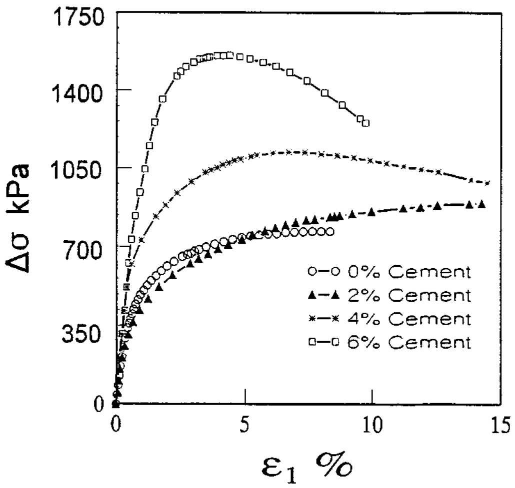

Figure 17. Effects of cement content on ε–σ relations for $\sigma_3 = 200$ kPa

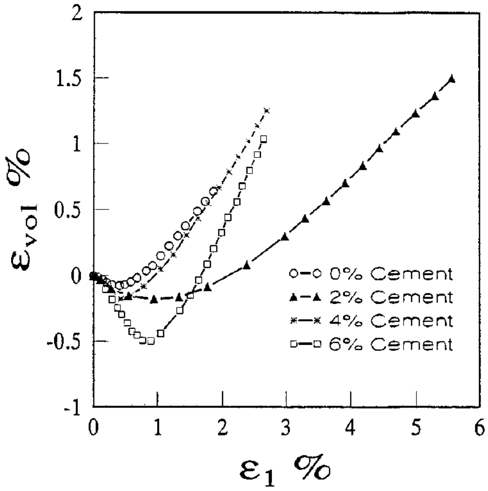

Figure 18. Effects of cement content on volumetric strains for $\sigma_3 = 200$ kPa

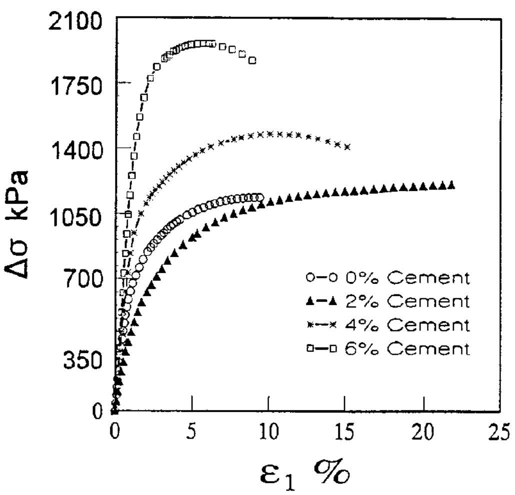

Figure 19. Effects of cement content on ε–σ relations for $\sigma_3 = 300$ kPa

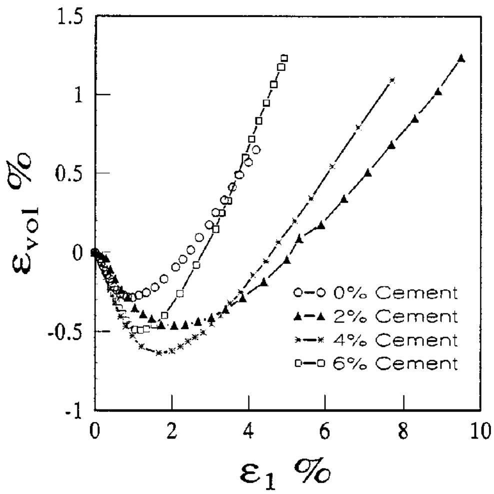

Figure 20. Effects of cement content on volumetric strains for $\sigma_3 = 300$ kPa

Increase of cement content results in a stronger, stiffer and more brittle material. It is interesting to note that significant post-peak softening is observed only for the 6 per cent cemented soil. Increase of confinement reduces the softening tendencies, and generally results in a more ductile response. It is also observed that the clean sand is somewhat stiffer initially than the 2 per cent cemented soil. This is the result of the specimen construction process which resulted in looser structure for the 2 per cent cemented sand, compared to the clean sand.

The effects of cement content on the strength are summarized in Figure 21 in terms of the conventional strength parameters c and ϕ. The most striking conclusions from Figure 21 are that cement content increases the cohesion in a non-linear way, while it does not change the friction angle for the range of confinement pressures that are examined here. A plot of the variation of cohesion with cement content is presented in Figure 22. The observed *non-linear* increase of cohesion with cement content is attributed mainly to the way cement coats the sand particle. As cementation tends to coat the sand particles evenly, parts of it coat particle surfaces that are facing the voids of the soil and thus do not contribute to the increase in shear strength. At low cement contents, this non-contributing proportion is large, while at larger percent of cement content the non-contributing proportion becomes smaller since the sand surface does not change. Other potential reasons include a more even distribution of cement, and a non-linear increase of points of contact for larger cement content.

The effects of cement content on the volumetric behaviour of soils can be examined in Figures 14, 16, 18 and 20. It seems that the ultimate dilation rate is not influenced significantly by the percentage of cement content. The exception to this rule comes from the 2 per cent cemented soils and is attributed to the lower initial densities of these specimens. It is also observed that the initial volumetric compression increases with increased cement content. To understand this, one must consider the internal structure of a cemented sand. Extreme cases of this structure are presented in Figure 23. Figure 23(a) represents a structure of large voids and significant internal collapse potential, while Figure 23(b) represent a dense frictional structure with little compression potential. The specimens that are studied here are fairly compacted and are thus closer to Figure 23(b). However, some structure similar to that of Figure 23(a) also exists and becomes more pronounced as the percent of cement content increases, and may be responsible for the observed increase in compressibility at the initial states of shearing.

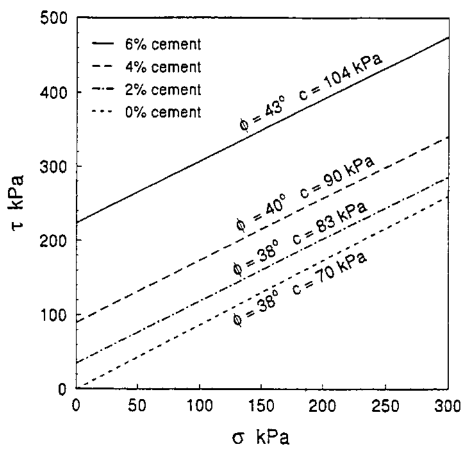

Figure 21. Effect of cement content on failure envelope

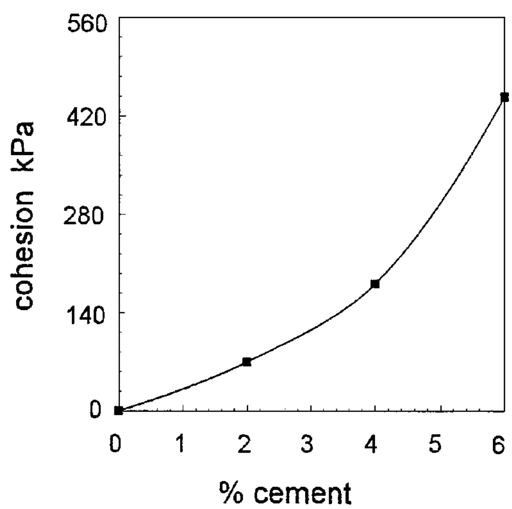

Figure 22. Effect of cement content on cohesion

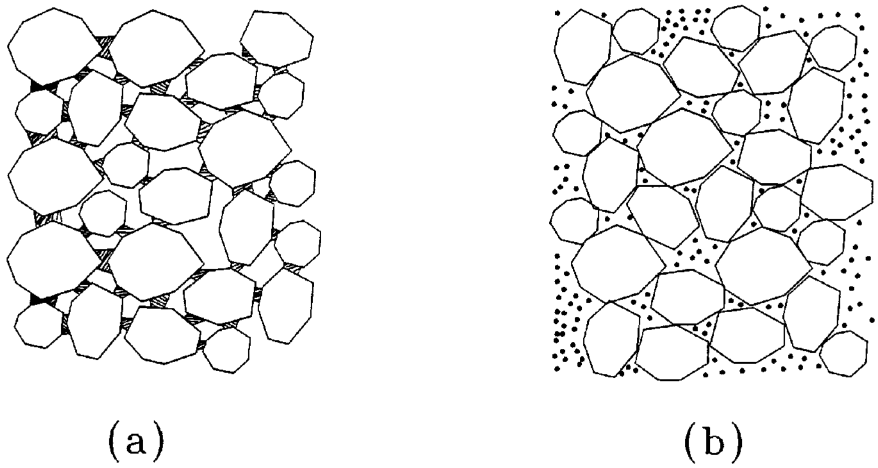

Figure 23. Extreme cases of internal structure of cemented sands

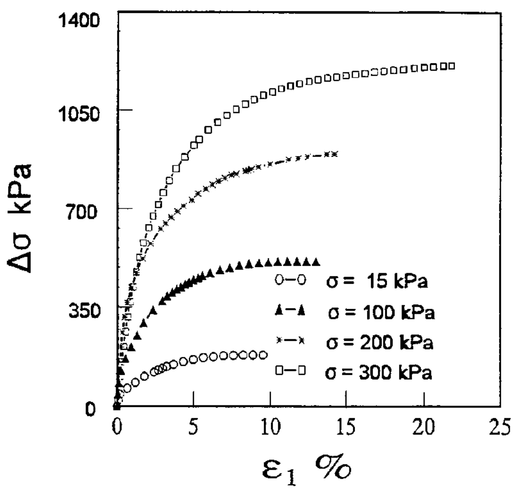

Figure 24. Effects of confinement on ε–σ relation of 2% cemented soil

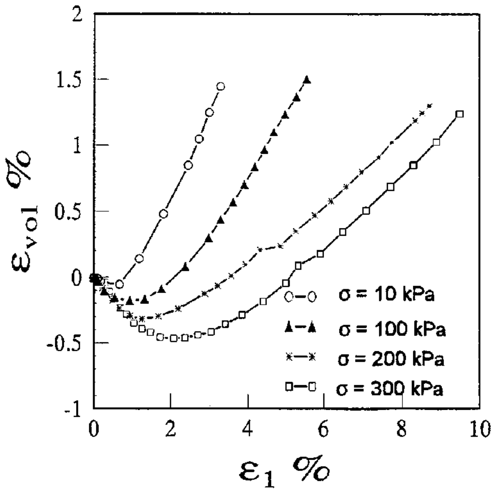

Figure 25. Effects of confinement on volumetric strains of 2% cemented soil

The effects of confinement on the stress–strain and volumetric response of cemented soils are illustrated in Figures 24–29. Increasing confinement causes a more ductile shear deformation, with larger initial volumetric compression and reduced ultimate dilation rate. The post-peak behaviour is in general characterized by some softening which is diminished as the confinement pressure increases.

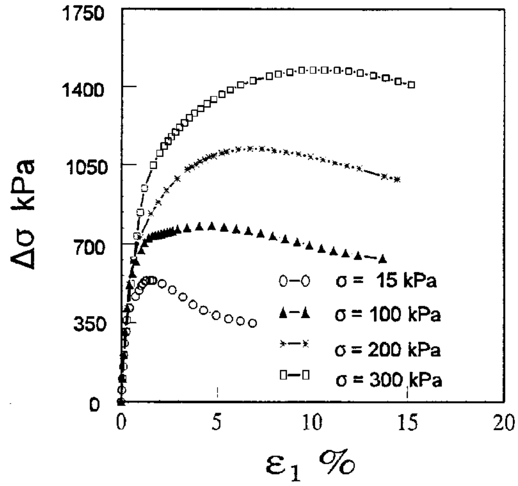

Figure 26. Effects of confinement on ε–σ relation of 4% cemented soil

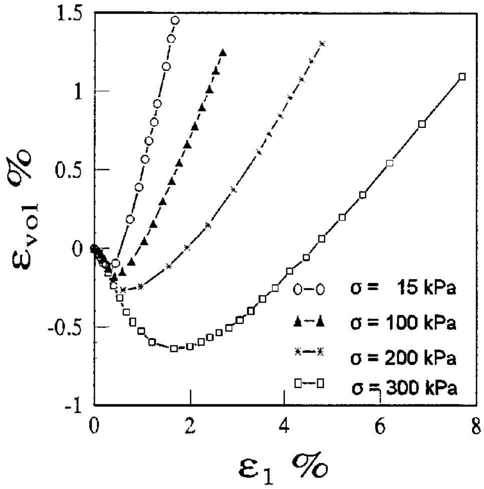

Figure 27. Effects of confinement on volumetric strains of 4% cemented soil

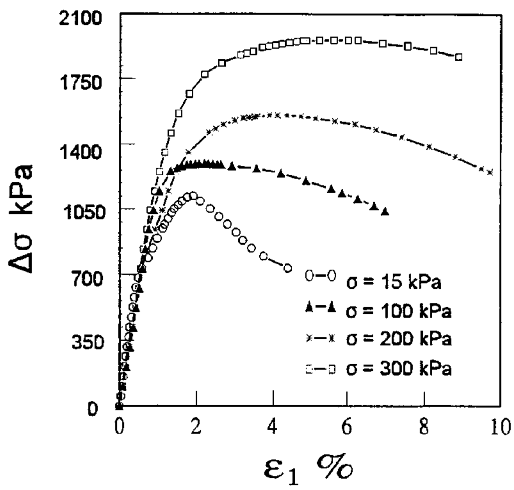

Figure 28. Effects of confinement on ε–σ relation of 6% cemented soil

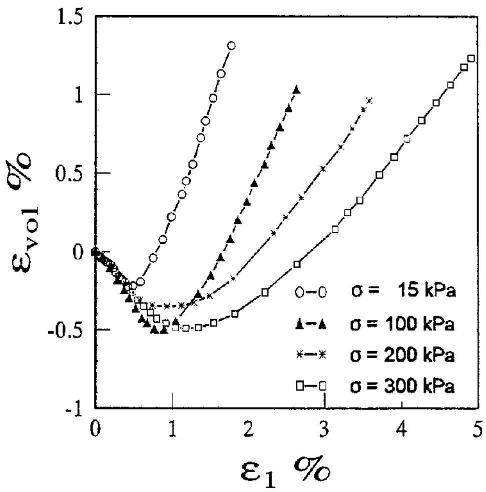

Figure 29. Effects of confinement on volumetric strains of 6% cemented soil

SUMMARY AND CONCLUSIONS

The following goals have been accomplished in this study: (a) determination of the appropriate triaxial testing procedures regarding specimen size, slenderness and end lubrication; (b) evaluation of the effects of cement content on the stress–strain–volume characteristics of sands; and (c) evaluation of the effects of confinement on the stress–strain–volume characteristics of cemented sands.

The conclusions of the experimental study carried out here are the following.

1. Large specimens of slenderness ratio equal to one are preferable if appropriate end lubrication measures are taken.
2. The cohesion of cemented sand increases non-linearly with cement content, while the peak friction angle remains practically unaffected.
3. The initial stiffness of a sand increases as a function of cement content.
4. The initial volumetric compression of a dilatant sand increases as a function of cement content, and confinement.
5. The ultimate dilatation rate of a dilatant sand is not affected significantly by the amount of cement content, while it decreases with increasing confinement.
6. Post-peak degradation of the shearing resistance of sands becomes more pronounced with increasing cement content and decreasing confinement.

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